ANNUAL REPORT ON THE STATE OF THE OCEAN AND THE OCEAN OBSERVING SYSTEM FOR CLIMATE

Executive Summary

This Annual Report is a compilation of articles, progress reports, and references focused on the current state of the ocean and the status of the ocean observing system for climate in fiscal year (FY) 2004. The report synthesizes observations integrated with models and scientific expertise to provide products to decision makers, the science community, and the public. This reporting framework establishes a formal mechanism for implementing a "user-driven" observing system and for reporting on the system's performance in meeting the requirements of operational forecast centers, international research programs, and major scientific assessments. Stakeholders are invited and encouraged to provide formal recommendations for system improvement and evolution.

Chapter 1 provides an introductory overview of the ocean and its role in climate with an explanation of the ocean's physical parameters that contribute to Earth's changing climate. Ocean-atmosphere interactions are addressed along with the impacts of climate change on sea ice extent and sea level. Connections are made between ocean observations and economic and societal impacts.

Chapter 2 includes a series of summaries focused on ocean climate from FY 2004 placed in historical context, reasons why it is increasingly important to monitor climate variables, accompanying climate applications, and how the observing system needs to be enhanced to improve ocean analysis and product development. Chapter 2 focuses on the products linked with the observing system, specifically sea level, ocean carbon, sea surface temperature, surface currents, air-sea exchanges of heat, momentum, and fresh water, heat content variations, and sea ice.

Chapter 3 focuses on the observing system and provides a compilation of all FY 2004 progress reports and work plans written by the project managers. These projects are focused on the mission of the Office of Climate Observation, namely, documenting long-term trends in sea level change, ocean carbon sources and sinks, the ocean's storage and global transport of heat and fresh water, and the ocean-atmosphere exchange of heat and fresh water, along with accompanying parameters.

Chapter 4 contains selected abstracts from refereed publications, and a bibliography of science articles and publications written by the scientific community during FY 2004 treating the global observation of ocean heat, carbon, fresh water, and sea level change.

*The State of the Ocean in 2004**

Global Sea Level Rise—L. Miller and B. C. Douglas

Satellite altimeter observations since 1993 show global sea level has risen almost steadily at a rate of 2.8 ±0.4 mm yr^{-1} (Fig. 1). This trend is significantly higher than the 20^{th} century rate of 1.8 ±0.3 mm yr^{-1} determined from tide gauge observations made over the past 50 to 100 years (Douglas 1997; Peltier 2001; Miller and Douglas 2004; Church et al. 2004; Holgate and Woodworth 2004; White et al. 2005). However, it is unclear whether the increased rate observed by satellite altimeters reflects a long-term change with respect to the historical rate, or some manifestation of inter-decadal variability.

A map of the altimeter-measured trends (Fig. 2) shows that all of the ocean basins experienced rising sea levels over the past decade, but large regional variations are also evident. The tropical western Pacific and Southern Oceans exhibited large positive trends (>10 mm yr^{-1}), while the Northern Pacific was distinctly negative. The geographical pattern of trends was roughly similar to that observed in the change in upper ocean heat content as determined from *in situ* hydrographic measurements (Cabanes et al. 2001) suggesting that, at least on decadal time scales, regional sea level trends have been largely controlled by thermal processes. Mean warming of the upper 750 m of the water column in all ocean basins can account for 1.6 ±0.2 mm yr^{-1} of global sea level change between 1993 and 2003 (Willis et al. 2004). This contrasts sharply with the average 20th century contribution to sea level rise from thermal expansion, estimated to be about 0.5 mm yr^{-1} (Antonov et al. 2002). The remaining portion of the total trend for the past decade, roughly 1.2 mm yr^{-1}, was likely due to the melting of grounded ice on Greenland and/or Antarctica and, to a lesser extent, from mountain glaciers, which is a result consistent with the average 20th century mass contribution to sea level rise estimated by Miller and Douglas (2004).

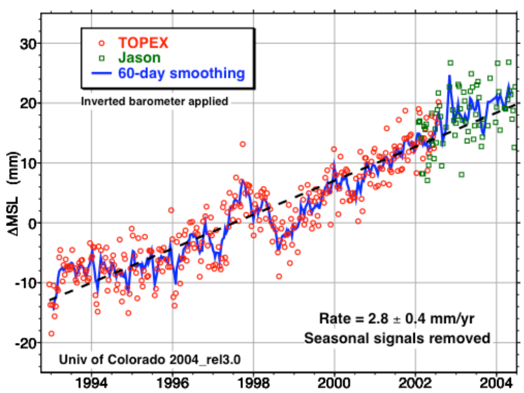


Figure 1. Global mean sea level variations determined using altimeter measurements from the TOPEX (1993-2002) and Jason-1 (since 2002) satellites. (Source: http://sealevel.colorado.edu; Leuliette et al. 2004).

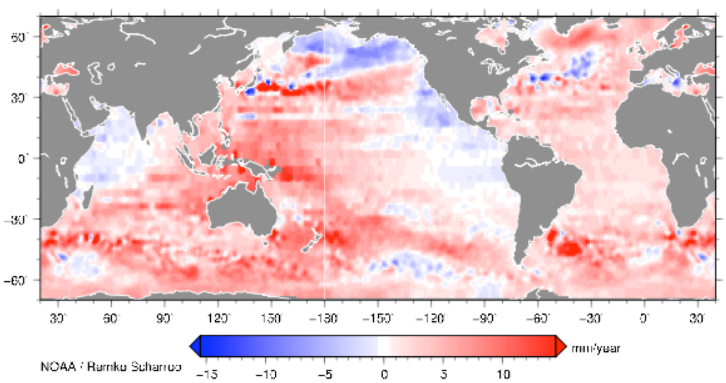


Figure 2. Sea level trends over the period 1993-2004 determined from TOPEX and Jason-1 satellite altimeter observations. The global mean of this map gives the 2.8 mm yr^{-1} value shown in Fig. 1.

Sea Surface Temperatures—R. W. Reynolds

Sea surface temperature (SST) variability during 2004 was examined using the weekly optimum interpolation (OI) analysis of Reynolds et al. (2002). This analysis combines in situ SST data (i.e., ship and buoy data) with satellite SST retrievals from the infrared (IR) channels of the Advanced Very High Resolution Radiometer (AVHRR). To clearly demonstrate the overall changes between 2004 and other years, a time series of the mean monthly OI SST anomaly from

75°S to 75°N was constructed for the entire period of record (Fig. 3). The general change over this period has been a slow warming with several large fluctuations of 1-3 years. The climatological base period used is 1971-2000 (Xue et al. 2003), so the overall warming tends to favor positive over negative anomalies toward the end of the record. Fluctuations of 1-3 years are usually due to the warm and cold SST anomalies in the tropical Pacific associated with strong El Niño and large La Niña events, respectively. Impacts from these events often influence the tropical Indian SST anomalies and may influence the tropical Atlantic SST anomalies, but the "phase" of the SST relationship appears to have varied. For example, the El Niño event of 1982-83 occurred along with cold tropical Atlantic SST anomalies, while the El Niño event of 1997-98 occurred along with warm tropical Atlantic SST anomalies. However, the SST anomaly curve was relatively flat from 2001 through 2004, which suggests that overall warming trends were small over this period and that no large El Niño or La Niña events occurred during this time.

The mean and standard deviation of the weekly anomaly for 2004 is shown in Figure 4. The mean anomalies in the upper panel show positive SST anomalies in the central Pacific, the North Atlantic and to a weaker extent, the tropical Indian Ocean and the western Indian Ocean near 35°S. The standard deviation of the anomaly (Fig. 4, lower panel) shows the strongest variability between roughly 30°N and 70°N, and in the eastern tropical Pacific. In addition, there was more modest variability along the equator in the eastern Pacific, and between 30°S and 50°S east of South America, and both east and west of the Cape of Good Hope near the southern tip of Africa.

The most important signal observed in 2004 associated with extra-tropical SST variability, which also occurred in 2003, was between the 60°N to 70°N latitude band. These positive SST anomalies between August and October were the oceanic response to large and warm summer and fall air masses, and their associated positive land surface air temperatures anomalies found along this same latitude band.

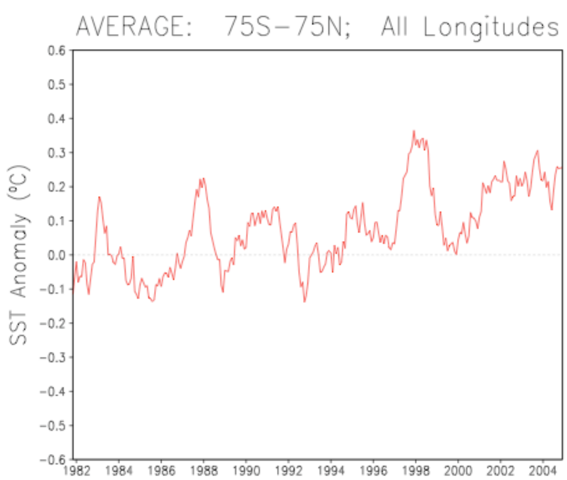


Figure 3. Time series of average monthly sea-surface temperature (SST) anomalies between 75°S and 75°N for the period November 1981 through December 2004. The anomalies were computed relative to a 1971-2000 base period.

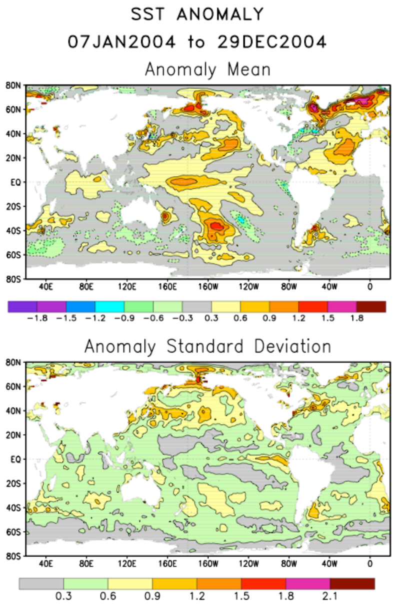


Figure 4. Weekly SST anomalies for the period 7 January 2004 through 29 December 2004: top) mean, and bottom) standard deviation. The anomalies were computed relative to a 1971-2000 base period. The contour interval used is 0.3°C, and the 0°C contour is not shown.

Ocean Heat and Fresh Water Content and Transports—L. Talley

Operational products of subsurface temperature and salinity fields are produced for the Atlantic basin, and the subsurface temperature field only for the North Pacific basin. Water temperature changes in the upper ocean had important regional variations in 2004, with warming in the subtropics and highest polar latitudes, and cooling at sub-polar latitudes in the northern hemisphere (both in the North Pacific and North Atlantic). Global ocean heat content calculated from combined data sets increased monotonically from 1993 to 2003 (Fig. 5), and since 1999 in the tropics.

Freshening of upper ocean waters around the high latitude North Atlantic has been reported over the past several decades (Dickson et al. 2003; Curry et al. 2003). The observed salinity decreases persisted into 2004 (not shown), along with continued thinning of Arctic sea ice. Freshening of surface and intermediate water north of the Antarctic Circumpolar Current, and increased salinity in surface waters south of the current over the past decade have also been observed.

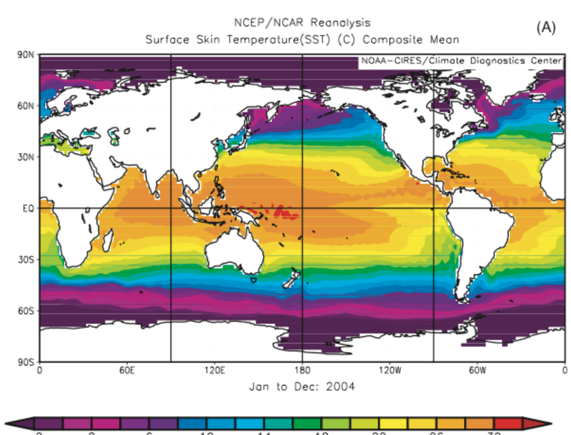


Figure 5. Total oceanic heat content (in J x 10^{22}) integrated over the tropics (green line) and the globe (red line). The figure was adapted from Willis et al. (2004).

Evolution of the 2004 El Niño—M. J. McPhaden

A weak El Niño developed in the second half of 2004 in the equatorial Pacific Ocean. Anomalous warming of the ocean mixed-layer and surface conditions was, for the most part, centered near the International Date Line, with near normal SSTs in the equatorial cold-tongue of the eastern Pacific and along the west coast of South America. SST anomalies in the Niño 3.4 index region (5°N-5°S, 120°-170°W) were approximately 0.8°C above average from August to December 2004. The Southern Oscillation Index (SOI) was consistently negative during the latter half of 2004 (-0.6 average index value during August-December), which is indicative of the warm phase of the El Niño/Southern Oscillation (ENSO). The near-equatorial trade winds were unusually weak west of the date line, associated with the elevated central and western Pacific SSTs and negative SOI values. In contrast, the trade winds in the eastern Pacific were near- to above-normal throughout much of 2004.

The 2004 El Niño event was unusual in that it followed the moderate amplitude 2002-03 El Niño by only one year (McPhaden 2004). Factors contributing to the development of the 2004 El Niño so quickly after the termination of the previous event are not fully understood. However, it is noteworthy that the 2002-03 El Niño was followed by an extended period of excess warm water volume (i.e., heat content) in the equatorial zone, which was atypical of conditions following most previous El Niños. It is likely that the presence of weak, positive heat content anomalies following the 2002-03 El Niño generated large-scale conditions favorable for the recurrence of another warm event earlier than would otherwise have been expected. Episodic westerly wind forcing (i.e., westerly wind bursts) in the boreal spring and summer of 2004 (Fig. 6) may have served as the stimulus for the development of the observed warm anomalies by displacing the western Pacific warm pool towards the east (e.g., Kessler et al. 1995).

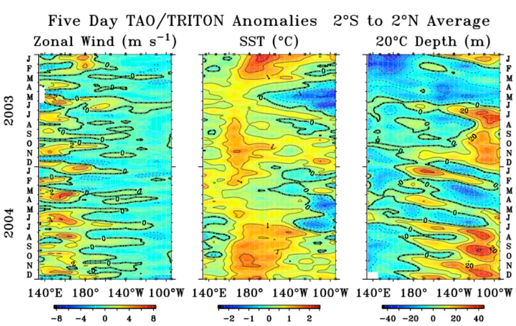


Figure 6. Five-day average anomalies of zonal wind, SST, and 20°C depth (which corresponds to the depth of the thermocline) relative to the mean seasonal cycle. The data were averaged over the 2°N–2°S region, and based on TAO/TRITON moored time series data. Tick marks on the horizontal axis indicate those longitudes sampled at the start (top) and end (bottom) of record.

Global Ocean Carbon Cycle: Inventories, Sources and Sinks—R. A. Feely and R. Wanninkhof

As a result of the measurements during the global CO_2 survey in the 1990s, and current improved methods of quantifying the anthropogenic CO_2 signal above the large natural background, the first measurement-based inventory of anthropogenic CO_2 in the ocean is now available (Fig. 7).

Anthropogenic CO_2 is unevenly distributed throughout the oceans, and the highest vertically integrated concentrations are found in the North Atlantic. The Southern Ocean south of 50ºS has very low vertically integrated anthropogenic CO_2 concentrations. Approximately 60% of the total oceanic anthropogenic CO_2 inventory is stored in the Southern Hemisphere oceans, roughly in proportion to the larger ocean area of this hemisphere. Approximately 30% of the anthropogenic CO_2 is found shallower than 200 m and nearly 50% above 400 m depth. The global average depth of the 5 μmol kg^{-1} contour is approximately 1000 m. Therefore, the majority of the anthropogenic CO_2 in the ocean is confined to the thermocline region.

From cruises in the North Pacific, the difference between the Repeat Hydrography measurements in 2004 and those from the World Ocean Circulation Experiment (WOCE) in 1994 quantitatively document changes of natural and anthropogenic CO_2 over the past decade. Significant increases in dissolved inorganic carbon (DIC) of up to 35 μmol kg^{-1} were observed in surface waters and in intermediate depths ranging from 200-1000 m. The increases are due to uptake of anthropogenic CO_2, changes in the strength of ventilation and biological processes, and the influence of eddies in the region. On average, mixed layer DIC increases of 1.5 ± 0.2 μmol kg^{-1} yr^{-1} were observed in the sub-tropical waters of the North Pacific over the past decade, indicating that the oceanic uptake of CO_2 in this part of the global oceans has been faster than the rate of growth of CO_2 in the atmosphere.

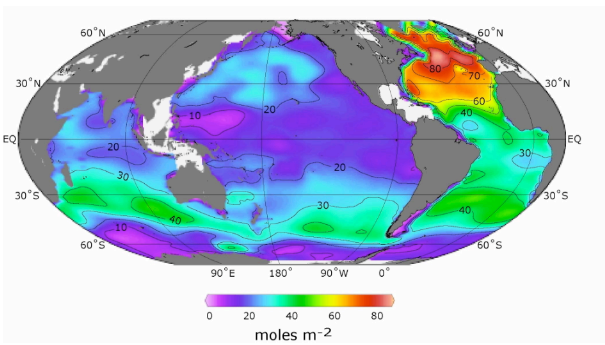


Figure 7. Column inventory of anthropogenic CO_2 in the ocean. High inventories are associated with deep water formation in the North Atlantic, and intermediate inventories with mode water formation between 30°-50°S. Total inventory of shaded regions is 106±17 Pg C (Sabine et al. 2004b).

Surface Current Observations—P. Niiler and N. Maximenko

The "*Global Drifter Program"* produces instrumental data records of the near surface velocity of the global oceans (Niiler 2001), which are maintained at NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) for all drifters (8049 as of July 2004).

The western tropical Pacific circulation injects significant surface water from the Philippine Sea to the South China Sea through the Luzon Strait (Centurioni et al. 2004) during the October-December periods of the northeast monsoon. Drifters have observed significant inter-annual changes of the patterns of this inflow. A comparison of the 2003 and 2004 drifter tracks during this monsoon period (Fig. 8) shows that the inflow in 2004 was much broader to the west, and stronger than observed in 2003. These changes were consistent with the altimeter observations of the differences of the sea level patterns in the Philippine Sea and the South China Sea.

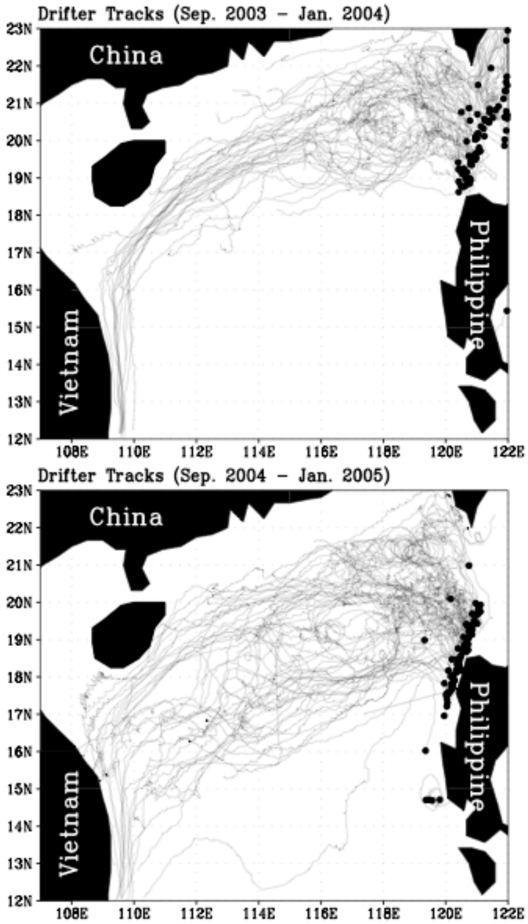


Figure 8. September-January tracks of Argos drifters that were released in the vicinity of the Luzon Strait in 2003-2004 (upper panel; 77 drifters – processed data) and in 2004-2005 (lower panel; 85 drifters – raw data). Note that significant interannual differences occurred in the north- south extent of the westward circulation in the South China Sea.

Sea Ice Extent and Thickness—I. G. Rigor and J. Richter–Menge

The annual average extent of Arctic sea ice has decreased by 8% over the past 30 years, and these decreases were larger (15–20%) during summer (ACIA 2004). The decline of Arctic Ocean sea ice has been attributed to the warmer air temperatures observed in the basin (e.g., Rigor et al. 2000; Jones et al. 1999), which may have thinned and decreased the extent of sea ice (ACIA 2004). However, there is also some evidence that changes in the circulation of sea ice on the Arctic Ocean driven by changes in winds over the Northern Hemisphere are important in explaining the recent minima in summer sea ice extent.

The last three summers have exhibited record low sea ice extent on the Arctic Ocean. The summer of 2002 set the record minimum for the Northern Hemisphere, while the summer of 2004 (Fig. 9; NSIDC 2004) had reduced sea ice over the Arctic Ocean than in 2002, but more sea ice was observed in the Canadian Archipelago and in the Laptev Sea. The age and thickness of sea ice explains more than half of the variance of the observed summer sea ice extent. The younger and thinner state of most of the sea ice on the Arctic Ocean persisted through 2004 (NSIDC 2004).

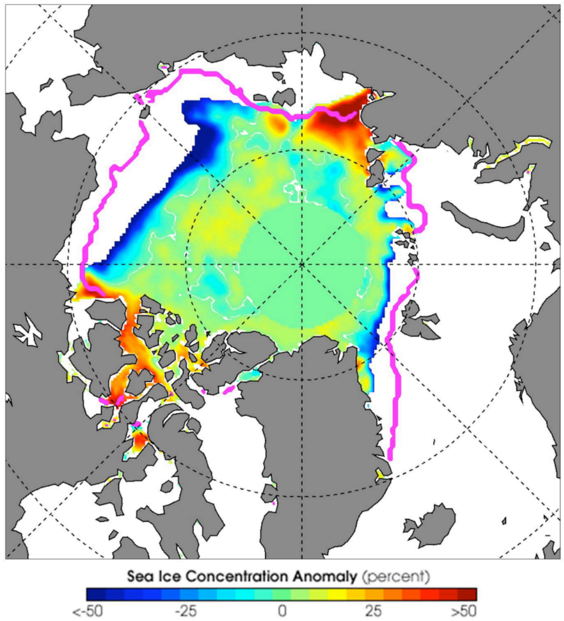


Figure 9. Sea ice concentration anomalies in September 2004 over the Arctic basin. The 2004 anomalies were estimated as the difference in sea ice concentration in 2004 with respect to the 1979–2000 base period. The pink line indicates the 1979-2000 median September ice edge. Anomalies are not calculated north of the circle centered over the pole (shown as light green) where satellite coverage prior to 1988 is unavailable. (Source: the National Snow and Ice Data Center, University of Colorado, Boulder; http://nsidc.org/news/press/20041004_decline.html).

***The State of the Global Ocean Observing System for Climate in 2004* – M. Johnson**

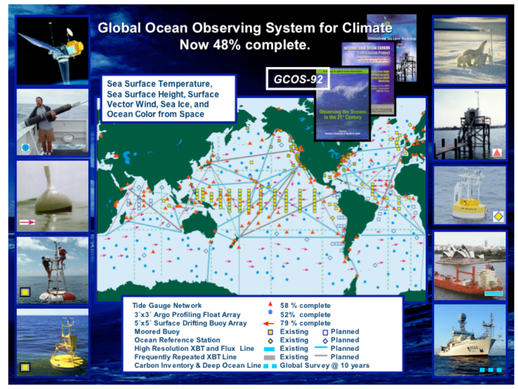
The observing system being put in place to meet climate requirements also supports global weather prediction, marine services, military applications, global and coastal ocean prediction, marine hazard warning systems (e.g., tsunami warning), and marine environmental monitoring, among other things. Many non-climate users also depend on the baseline composite system that is nominally referred to as the global ocean observing system for climate.

NOAA's Climate Observation Program provides a major part of the global component of the U.S. Integrated Ocean Observing System (IOOS) and the ocean baseline of the Global Earth Observation System of Systems (GEOSS). The global ocean observing system for climate is composed of moored and drifting buoys, Argo profiling floats, tide gauge stations, trans-oceanic ship lines, data and assimilation subsystems, and continuous satellite missions. The Climate Observation Program focuses on advancing the in situ networks and associated data and modeling components. The goal of the Program is to build and sustain a global observing system that will respond to the long-term observational requirements of the operational forecast centers, international research programs, and major scientific assessments.

The overarching priority is to achieve global coverage. In 2004 incremental advances were accomplished across all of the observing system networks. The system advanced from 45% complete in FY 2003 to 48% complete in FY 2004 (Fig. 10).

NOAA's contributions to implementation of the global ocean observing system are managed by 19 distributed centers of expertise at the NOAA Labs, Centers, Joint Institutes, universities and with business partners. These include AOML, PMEL, ETL, JIMAR (University of Hawaii), JIMO (Scripps Institution of Oceanography), CICOR (Woods Hole Oceanographic Institution), JISAO (University of Washington), CIMAS (University of Miami), CICAR (Columbia University), NCDC, NODC, CO-OPS, AMC, PMC, NDBC, NCEP, FSU (Florida State University), and SAI (Service Argos Inc.). The "System" is centrally managed at the Office of Climate Observation (OCO), a project office within the NOAA Climate Program Office.

Figure 10. A schematic of the global ocean observing system representing 48% completion. The ten small icons surrounding the map represent the array of instruments and platforms enabling monitoring of our global ocean.



International and interagency partnerships are central to the NOAA climate observing system implementation strategy. All of NOAA's contributions to global observation are managed in cooperation internationally with the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM), and nationally with the U.S. Integrated Ocean Observing System (IOOS). NSF has initiated their Ocean Observatories Initiative (OOI), which will potentially provide significant infrastructure in support of ocean climate observation, beginning in FY 2006. Commencement of an ongoing NSF-NOAA cooperative project for CLIVAR-carbon ocean surveys has proved to be an interagency-international-interdisciplinary success. ONR maintains a GODAE data server at Monterey that needs to be sustained after the experiment period (2003-2007) as permanent international infrastructure. NOAA ships and the UNOLS fleet provide ship support for ocean operations and NASA's development of remote sensing techniques is vital.

The observing system delivers "up front" information to the forecast centers, research programs, and assessments. In 2004, the first *Annual Report on the State of the Ocean and the Ocean Observing System for Climate* for fiscal year 2003 was produced as a demonstration project; it proved highly successful; the project will be continued documenting the state of the ocean and reporting on observing system progress annually. The annual reports include sections targeted for three audiences: 1) decision-makers and non-scientist, 2) scientists, 3) observing system managers.

The second Annual System Review was conducted April 13-15 in Silver Spring, Maryland. This meeting brought together project managers to discuss system-wide issues and engage in program strategic planning. It also provided the annually scheduled forum for observing system users to provide feedback and discuss their requirements and recommendations for system evolution with the project managers. Review of the NDBC and PMEL plan for transition of TAO operations from PMEL to NDBC was a major topic of discussion during the 2004 Annual Review. The issue of the gap in delivery of ocean analyses as an end product of ocean observations was also a major part of the strategic discussions. The Climate Observation Program in FY 2005 will begin a program of ocean analysis work to ensure that this gap gets filled.

In cooperation with the international GCOS program office in Geneva, the OCO developed a special web page in support of the GCOS *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC* (GCOS-92). The OCO web page, www.oco.noaa.gov/page_status_reports_global.jsp, provides up-to date global maps and summary statistics from JCOMMOPS and other observing system partners contributing to international implementation of GCOS-92.

A demonstration project was initiated at OCO in cooperation with the GOOS Program Office at UNESCO and JCOMMOPS in Toulouse, to routinely report on progress of the observing system and contributions by countries. A consolidated report is now available on the OCO web site, accessible via the international portal at www.jcommops.org/network_status, which lists the 64 countries and the European Union that maintain elements of the composite ocean observing system and the number of platforms and expendables contributed by each country. This report allows tracking of progress toward international implementation of the ocean system specified in GCOS-92.

* References cited in the *State of the Ocean in 2004* section of this Executive Summary can be found at the end of each expanded article in Chapter 2 of this Annual Report.